FORECASTING STOCK-SPECIFIC UPRIVER MIGRATION TIMING OF CHINOOK SALMON IN THE YUKON RIVER

By

Bryce Douglas Mecum, B.S.

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APPROVED:

Milo D. Adkison, Committee Chair
Terrance J. Quinn, II, Committee Co-Chair
Toshihide Hamazaki, Committee Member
Phillip R. Mundy, Committee Member
Gordon H. Kruse, Chair
Department of Fisheries
S. Bradley Moran, Dean,
College of Fisheries and Ocean Sciences
Michael A. Castellini,
Dean of the Graduate School

Abstract

Pacific salmon (*Oncorhynchus spp.*) are an economically and culturally important genus of fishes endemic to the North Pacific. Their sustainable management depends on an understanding of the drivers of their abundance and migration dynamics. In many instances, statistical models are employed to predict abundance and run timing before harvest takes place to more effectively meet management objectives. In this thesis, I created a general-purpose predictive model of run timing that can be applied to many salmon populations. I then applied it to Yukon River Chinook salmon (*O. tshawytscha*) by generating pre-season predictions of inriver run timing, which I then compared with existing observations of run timing at two upriver locations. Prediction errors were low enough for the model to be useful to management. Models such as the one created in this study represent an objective tool that can be used to reduce subjectivity in fisheries management.

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Introduction

Chinook salmon (*Oncorhynchus tshawytscha*) are an anadromous fish species endemic to the North Pacific rim (Healy 1991). They are the longest-lived and largest member of the Pacific salmon (*O. spp.*) and can undergo extensive migrations across oceans and within freshwater ecosystems. Juveniles spend one or more winters in freshwater and then migrate to the ocean, where they spend as many as five years before returning to natal streams and rivers to attempt to spawn (Healy 1991). Numerous stocks of Chinook salmon are distributed throughout Alaska, ranging from Southeast Alaska to the northern portion of Western Alaska (Healy 1991). In Alaska, Chinook salmon are harvested in subsistence, personal use, commercial, charter, and sport fisheries. Along with their social importance, Chinook salmon are an important food resource for marine and terrestrial predators such as killer whales (*Orcinus orca*), grizzly bears (*Ursus arctos horribilis*) and wolves (*Canis lupis*) (Ford & Ellis 2006, Adams et al. 2010, Levi et al. 2012).

Accurate management of Chinook salmon fisheries by allowing enough adult fish to migrate to spawning grounds is essential to sustainably maintaining this resource. Management of Chinook salmon within Alaska is the responsibility of the Alaska Department of Fish & Game (ADFG). ADFG operates weirs, towers, sonar sites, and smolt traps to monitor inriver salmon populations as juveniles and adults. Management is typically based on spawning escapement goals which are most commonly achieved through opening and closing fisheries by emergency order during the season to control harvest (Clark et al. 2006). Fisheries for Chinook salmon are prosecuted with a variety of gear types including gill net, hand and power troll, fish wheel, dip net, and hook-and-line.

In Alaska, harvested stocks of Chinook salmon have declined in abundance over the last two decades (ADF&G Chinook Salmon Research Team, 2013) and, as fish become less abundant, the diverse user groups of this resource are faced with increased fishing restrictions. Because of the importance of accurate management of Chinook salmon, there is a great need for creating tools to aid managers in making decisions about where, when, and how to harvest them. In this thesis, I created a general purpose movement model and applied it to Yukon River Chinook salmon, where it can be used to direct harvests away from weaker stocks. The Yukon River hosts one of the largest populations of Chinook salmon, which also has the most extensive inriver migration of the species.

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Chapter 1: Forecasting Stock-Specific Upriver Migration Timing of Chinook Salmon in the Yukon River[1]

1.1 Abstract

In fisheries with multiple stocks and sequential harvesting in multiple fishing districts, fish from stocks migrating through a greater number of fishing districts may be subject to a greater degree of cumulative fishing mortality. Knowledge of stock-specific migratory patterns through fishing districts is therefore a crucial component to management of these fisheries on a stock-specific basis. For the Chinook salmon run on the Yukon River, Alaska, there are three major stock groupings; each of which migrates through a different number of fishing districts and has different migratory patterns. In this study, we developed a series of models to take advantage of existing data on run timing, genetic stock composition, and radio telemetry to generate stock-specific, pre-season forecasts of inriver run timing at any upriver location of interest. To test the accuracy of these models, we compared predicted run timings to observed run timings at two upriver sites using a hindcasting approach. For both upriver locations, mean absolute prediction errors (MAPE) of median run timing were small (MAPE 2.33 days ±SD 1.10 days and MAPE 2.00 days ±SD 1.41 days). The fit between the observed and predicted run timing distributions was generally good across years, though variable. We describe a general framework under which these models could be modified and used under a variety of scenarios and how a modeling framework like the one presented in this study can be used as the basis for future research.

1.2 Introduction

Pacific salmon (*Oncorhynchus spp.*) are hatched in freshwater, migrate to the ocean as juveniles, and finally return to freshwater to spawn (Groot & Margolis 1991, Quinn 2005). During this return migration, they are typically harvested either in coastal areas or within the freshwater

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[1] Bryce D. Mecum, Milo D. Adkison, Terrance J. Quinn, II, Toshihide Hamazaki, Phillip R. Mundy. 2015. Prepared for submission to the North American Journal of Fisheries Management.

bodies of their natal tributaries. For some stocks of Pacific salmon, harvest occurs in multiple, sequential fishing districts, and individual fish may be subject to harvest in numerous fishing districts before reaching their spawning grounds. When a salmon run is composed of multiple stocks of the same or different species, fish from the different stocks often migrate through a different number of fishing districts along a river system. Thus, the cumulative effects of fishing mortality may differ greatly across stocks, with the farthest migrating stocks being subject to the greatest degree of cumulative fishing mortality. If different stocks co-migrate through a district, it may not be possible to independently target fish from a particular stock. Without knowledge of stock-specific differences in migration patterns, harvest effort would need to be lowered for districts with a greater number of stocks migrating through them.

Managing salmon harvest on the Yukon River in Alaska is a complex issue because the run of Chinook salmon (*O. tshawytscha*) is comprised of three major stocks that co-migrate with one another and with other species of Pacific salmon (Evenson et al. 2009, Eiler et al. 2014, 2015). Subsistence, commercial, and sport fisheries for these stocks occur within six principal fishing districts (Figure 1) located within the state of Alaska and in the upper reaches of the river within Canada (Evenson et al. 2009). Fishing for Chinook salmon in the Alaskan portion of the river is managed by the Alaska Department of Fish & Game (ADFG) and is typically prosecuted by gillnet or fish wheel. Fishing effort is controlled through a combination of time-and-area closures and mesh size restrictions (Evenson et al. 2009). The degree of fishing effort is a function of the managers' pre-season expectation of total run size, adjusted by in-season data collected from test fisheries located on the river delta, a lower-river sonar project, and other sources of in-season fisheries data collected upriver. Achieving management targets is difficult because stock-specific catch and catch for the run as a whole are unknown until after the run is over. Stock-specific information about the relative migratory timing of Chinook salmon stocks moving through each fishing district would help managers differentially target stocks, resulting in a more consistent harvest rate on each.

Under current management, the upriver movement of salmon is predicted by observing pulses, or large spikes in daily counts, of fish passing one of two lower-river assessment projects (Estensen et al. 2015). These pulses of fish are assumed to move upriver at rates that have been determined from historical time lags between pulses of fish passing lower river assessment projects and pulses subsequently observed at upriver assessment projects. This approach has three main limitations. First, pulses entering the lower river contain fish from multiple stocks and tracking movement this way limits the manager's ability to manage on a stock-specific basis. Second, the stock composition of pulses entering the river is of an unknown mixture of stocks but the stock composition of pulses at upriver locations is always of a single stock, making the comparison of pulses potentially invalid. Third, Eiler et al. (2015) showed that the groupings of salmon in a pulse do not migrate upriver as a cohesive group and thus lower river and upper river pulses may not be related. Given these limitations, a predictive model of upriver movement that is not based on tracking pulses may more accurately describe how stocks migrate upriver, benefiting managers and users. Current management practices, while empirically effective, are largely subjective and the model proposed in the present study would offer an objective method for forecasting inriver run timing.

Stocks of Yukon River Chinook salmon vary with respect to their river entry timing (DeCovich & Howard 2010, Eiler et al. 2014) as well as their upriver migratory patterns (Eiler et al. 2015). Generally, fish from stocks migrating to farther-upriver reaches tend to arrive earlier and swim faster than fish from lower-river reaches. As an example, Eiler et al. (2014, 2015) found that fish from the upper basins typically arrived in mid to late June and traveled 52 – 62 km d^{-1}, whereas fish from the lower basins in early July and traveled 28 – 40 km d^{-1}. They also found that fish from a particular stock had variable movement rates across reaches. These differences in river entry timing and upriver migratory patterns suggest that models could be created to assist management in harvesting stocks selectively.

In this study, our goal was to create a series of models to generate pre-season forecasts of stock-specific run timing of Yukon River Chinook salmon at any location of interest within the Yukon River. Two specific objectives were: (1) predicting entry timing for the run as a whole and (2) predicting stock-specific run timing at any upriver location. To test the models from each objective, we used a hindcasting approach to assess both of the assumptions built into the models and to estimate the accuracy of future predictions from the models. Due to limited availability of accurate upriver run timing information, we were only able to estimate prediction accuracy for the Canadian stock. We then discuss the forecasting framework under which these models could be used and the potential for their application to other species within the Yukon River as well as on stocks elsewhere.

1.3 Methods

1.3.1 Study Site

The Yukon River is the third longest river and fourth largest drainage basin in North America (Brabets et al. 2000). It runs over 3,300 km from its headwaters in northwestern British Columbia, Canada westward across the interior of Alaska to its mouth at the eastern Bering Sea. The Yukon River hosts considerable runs of the five major Pacific salmon species (Evenson et al. 2009), but the focus of the present study is Chinook salmon. Chinook salmon on the Yukon River are jointly managed by the Alaska Department of Fish & Game (ADFG) and the Canadian Department of Fisheries and Oceans (DFO). On the Alaskan side of the river, Chinook salmon are harvested in sequential, or gauntlet (Starr & Hilborn 1988, Brannian 1990), fisheries, where migrating salmon pass through multiple, sequential fishing districts on their way to their spawning grounds. ADFG divides the Alaskan portion of the river into six fishing districts (Figure 1) and controls harvest through time-and-area closures at the district or sub-district level.

1.3.2 Data

Run Timing

Three sources of run timing data were used in the present study for three different purposes: (1) modeling entry into the river, (2) modeling stock-specific run timing in the lower portion of river, and (3) estimating the accuracy of the inriver forecasts of run timing. Here, run timing refers either to daily time series of absolute counts or estimated catch per unit effort (CPUE) of fish passing a particular location. The term ‘entry timing’ is used to distinguish run timing at or near the river mouth from run timing at inriver locations. All run timing data were converted from absolute counts or CPUE into proportions of the annual total to standardize run timing across sites and years.

To characterize entry timing, CPUE data were obtained from a time series of commercial fisheries (1961 – 1979) and test fishing (1980 – 2014) catches from LYTF (abstracted from materials publicly available from the Alaska Department of Fish and Game). CPUE was calculated as the catch per 100 fathoms of gill net fished for one hour and were converted to daily proportions prior to analysis. Median run timing was calculated as the date by which 50% of the total cumulative CPUE observed at LYTF in a given year was observed. Dates of median run timing were expressed in terms of date in June where June 1 = 1, June 2 = 2, etc. to simplify analysis.

To characterize stock-specific run timing in the lower portion of the river, genetic stock composition and run timing data were obtained from an ADFG-operated sonar project located near the village of Pilot Station, Alaska (Pilot Station sonar) at river km 198. Run timing data have been generated at this project since 1986 but genetic sampling and estimates of stock composition were only available for recent years (2007 – 2014), so only run timing data from 2007 – 2014 were used. Methods for estimating stock composition can be found in Templin et al. (2006).

To determine the accuracy of inriver forecasts of run timing, run timing data were obtained from two upriver locations: Rapids (fish wheel) and Eagle (sonar). These two locations were chosen because of the close correspondence between the fish passing them and one of the stock groupings with genetic stock composition data. As a result of their far upriver location, run timing data from these sites can only be used against predictions for the Canadian stock.

Rapids fish wheel (river km 1176) is a modified fish wheel that counts Chinook salmon and other species of fish using 24-hour video and has been operated since 2000 by Stan Zuray with funding from the United States Fish and Wildlife Service (Zuray 2003). Run timing data from this site are daily CPUE's expressed as the number of Chinook salmon counted in 24 hours. The second inriver location used to measure accuracy of the upriver forecasts is Eagle sonar (river km 1223) which is located near the village of Eagle, Alaska and has been operated by the ADFG since 2005. Run timing data from this site are estimated daily counts of Chinook salmon passing the sonar site. Both data series were converted to proportions of the total run prior to analysis

Environmental Data

Environmental data used to model entry timing were updated time series of the three variables used in Mundy & Evenson (2011): air temperature, sea surface temperature, and ice cover. For air temperature, April mean air temperature (AIR) data were obtained directly from web published tables from a land-based weather station in Nome, Alaska (US National Weather Service, Alaska Region) and were available from 1961 – 2014[2]. May mean daily sea surface temperature (SST) was computed from daily measurements of sea surface temperature (SST) at 63.1°N 165.5°W. These measurements (1961 – 2014) were derived from the NCEP reanalysis model (Kalnay et al. 1996) by N. Bond (NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA) through 2009 and by Will Koeppen (Axiom Data Science, Anchorage, Alaska, USA) thereafter. Average daily sea ice concentration (ICE) 1970 – 2014 over the region 62-63°N by 166-169°W were computed by Jinlun Zhang (Applied Physics Laboratory, University of Washington, Seattle, WA, USA) through 2009 using satellite ice concentration data from the National Snow and Ice Data Center (NSIDC) and by Will Koeppen (Axiom Data Science, Anchorage, Alaska) thereafter. Daily ice concentrations were measured from the vernal equinox (March 20 in most years) through the end of May.

Genetic Stock Composition

Genetic stock composition estimates were obtained from fish tissue samples taken at a sonar project operated by ADFG near Pilot Station, Alaska (DeCovich & Howard 2010). A test fishery is operated in tandem sonar equipment in order to apportion sonar counts by species and this test fishery also collects data on age, sex, length, and genetics. During the season, random samples of

[2] http://www.ncdc.noaa.gov/cdo-web/datasets/GSOM/stations/GHCND:USW00026617/detail

Chinook salmon taken in the test fishery have their axillary processes clipped, preserved and sent to the ADFG Gene Conservation Laboratory in Anchorage, Alaska. From these samples, genetic stock composition estimates are generated by mixed stock analysis using a 26-SNP (single nucleotide polymorphism) baseline developed by ADFG, which results in stock composition estimates at three hierarchical spatial stock groupings. The finest-scale grouping for which stock compositions estimates were available for all years was the "broad-scale" grouping, which differentiates between Canadian, Upper Yukon, and Lower Yukon Chinook salmon and are available from 2007 – 2014 (Table 1). These estimates of stock composition are generated from samples aggregated over a period of time (usually 1-2 weeks); these periods are generally chosen to match discrete pulses of Chinook salmon passing the sonar site (Estensen et al. 2015). Chinook salmon passing this sonar project are often observed passing in three or more somewhat distinct pulses and, as a result, there are usually between three and four reporting periods per year.

Radio Telemetry

Radio telemetry data were from a 2002 – 2004 study where 2,860 Chinook salmon were radiotagged near the lower-river village of Russian Mission (river km 343; Eiler et al. 2014, 2015). In this study, fish were tracked upstream of the tagging site using a combination of satellite-linked remote tracking stations and aerial surveys (Figure 2). Negative impacts of the tagging procedure were considered to be minimal as 98% of tagged fish resumed upriver movement and independent measures of movement indicated that movement rates for tagged and untagged fish were similar (Eiler et al. 2014, 2015). Data from each of the three years were pooled as estimates were not substantially different among years. From these data, average stock-specific movement rates between each of the Yukon River main stem tracking stations were calculated resulting in five reach-to-reach movement rates (Figure 2).

1.3.3 Entry Model

To forecast entry timing for the run as a whole, we slightly modified the approach of Mundy & Evenson (2011) to obtain better forecast accuracy. The suite of explanatory variables in the best model chosen by Mundy & Evenson (2011) was the result of model selection using correlationcentric model selection criteria (i.e., adjusted coefficient of determination). In this study, we re-ran model selection using forecast-centric model selection criteria (i.e., mean absolute prediction error or MAPE) in order to come up with a model more suitable for forecasting. MAPE was used because it is easy to interpret due to sharing units with the data used to calculate it. Model selection was performed using a hindcasting approach. Here, hindcasting refers to the process of generating a set of predictions for a set of years from a single model where, for a given year's prediction, the model was only fitted to data available prior to the year being predicted. This approach simulates the forecasting scenario under which these models will be used by managers, in which the model will be fit to all the data available prior to the run but not to the data from the upcoming run itself.

Candidate models included all possible combinations of the three previously-used explanatory variables investigated by Mundy & Evenson (2011): AIR, SST, and ICE. For each candidate model, hindcasted predictions and corresponding approximate 95% normal confidence intervals (+/- 1.96 model SE) of median entry timing were calculated for years 2000 – 2014. Two model selection criteria were then calculated for each model: (1) Mean absolute prediction error (MAPE), and (2) the proportion of observed median entry timings within the approximate 95% normal confidence interval (PROP). We also calculated the width of the prediction interval (INTWIDTH) for each model as a check to see if an individual model's confidence interval included more observations merely due to having a larger confidence interval. The best model was the model having the best combination of low MAPE and high PROP, while simultaneously having a confidence interval small enough to be useful to managers. This model is hereafter referred to as the Entry Model.

1.3.4 Within-Year Distribution of River Entry Dates

To construct stock entry timing distributions for each of the three stock groupings, we used a combination of run timing and genetics data from Pilot Station sonar. For each year y and stock s, daily proportions of the total run, p_{yd}, were multiplied by the corresponding daily estimate of genetic stock composition, g_{syd}, to yield the proportion of the run entering on day d in year y that belong to stock s:

$$s_{syd} = p_{yd} \times g_{syd}.$$

These values were then re-scaled to obtain the proportion of the stock entering on day d in year y:

$$\tilde{s}_{syd} = \frac{s_{syd}}{\sum s_{syd}}.$$

These values were then normalized to account for differences in annual run timing by subtracting out the annual median date of entry for the run as a whole in year y, m_y, from the dates:

$$\tilde{\tilde{s}}_{syd} = \tilde{s}_{syd} - m_y.$$

Finally, the set of $\tilde{\tilde{s}}_{sdy}$ were averaged across year to yield three average stock entry timing distributions, $\bar{s}_{sd}$. The forecasted stock-specific run timing in any given year is then created by shifting these distributions by the given year's predicted median entry date.

1.3.5 Inriver Model

The inriver model takes as input (1) the forecasted stock-specific within-year distribution of river entry dates, (2) a set of stock-specific reach-to-reach movement rates, and (3) the date for which we are forecasting the stock's position. The basis is the equation $d = rt$, where d is the distance traveled, r is the rate of travel, and t is the time traveled. The equation was modified to model the movement of a stock through multiple, sequential, non-overlapping reaches along a river. Reaches here could correspond to the segments of the Yukon River bounded by the remote tracking stations in Eiler et al. (2014, 2015) and this would allow simulated fish to move at different rates in each reach as they did in that study. This method differs from run reconstruction (Schnute & Sibert 1983, Starr & Hilborn 1988, Cave & Gazey 1994, Templin et al. 1996), in that the position of fish is expressed in a continuous fashion along the migratory route rather than in discrete bins such as fishing districts. The reason for this choice was two-fold. First, the tracking stations used by Eiler et al. (2014, 2015) did not align with the principal fishing districts commonly used by ADF&G and, second, managers on the Yukon River have the ability to open and close the fishery on a sub-district level and, thus, a flexible model was desired. The lowest reach, from Paimiut to MS-Anvik (Figure 2) is upriver of the location where the forecasting process begins (Pilot Station sonar) by 207 km so the first reach was extended downward to Pilot Station sonar.

First, we establish the parameters of the river and fish movement. For clarity, the subscript for stock is left out of the following equations but both the number of reaches, reach lengths, and travel rates are implicitly stock-specific. Let N be the total number of reaches in the migratory pathway, where the reaches are continuous and non-overlapping. Let d_i be a vector of length $N+2$ containing the length (in km) of each reach and r_i be a vector of length $N+2$ containing the travel rates (in km/day) that fish travel when in each reach. The first and last elements of d_i and r_i are set to dummy values which simplifies the notation and allows fish to travel upriver beyond the end of the final reach. The first element of the two vectors represents a virtual pool of fish that have not yet entered the river and have values $d_0 = 0$ and $r_0 = 1$. The last element of the two vectors represents the portion of the river upstream of the final reach and d_{N+1} is set to an arbitrarily large value (e.g., 200,000) and $r_{N+1} = r_N$.

The position of the cohort entering on day c, on day of the run d, is calculated as

$$p_{cd} = \sum_{i=0}^{N+1} d_i \times f_i,$$

where i is the reach, N is the total number of reaches, d is the length of reach i in km, and f_i is the proportion of reach i the cohort has traveled through. The f vector was calculated for each cohort c and day d in the following manner. First, let $t_i = d_i / r_i$ be the time, in days, it takes to travel through reach i and

$$T_i = \sum_{j=0}^{i} t_j$$

is the cumulative travel time, in days, to travel completely through reach i. Then let R be the reach in which the cohort entering on day c is in on day d, which is the equal to the greatest i where $d - c + 1 > T_i$. Then initialize the f vector such that all indices are equal to zero. Finally, set all $f_i = 1$ where $i < R$ and then set

$$f_{Rcd} = \frac{(d - c + 1 - T_R) \times r_R}{d_R}.$$

For example, a cohort from stock *s* that has entered the river ($f_0 = 1$), traveled completely through reaches 1 and 2, and traveled half-way through reach 3 would have an f vector of

$$f_{Rcd} = \{ 1, 1, 1, 0.5, 0, 0, 0 \}.$$

Generating Inriver Forecasts

Pre-season forecasts of inriver run timing were created in a step-wise fashion, beginning with predicting river entry timing and ending with stock-specific upriver run timing. First, the pre-season forecast of median entry timing, e_{sy}, for stock s and year y was created using the best model described in section 1.3.3. Then, three days travel time between LYTF and Pilot Station sonar was added. This travel time of three days is the historical difference in median run timing between LYTF and Pilot Station (1986 – 2014) and was calculated using the run timing data in 1.3.2. It was then rounded to the nearest integer to accommodate the model. Thus, the pre-season forecast of stock-specific run timing at Pilot Station sonar for stock s in year y was,

$$a_{sy} = \bar{s}_{sd} + e_{sy} + 3,$$

and named the arrival distribution in the Inriver Model, where a_{sy} is the forecasted arrival distribution, $\bar{s}_{sd}$ is the average stock-specific entry timing distribution, and e_{sy} is the forecasted median entry date of stock s in year y. To forecast upriver run timing and median run timing, the Inriver Model was applied where the day being forecasted was incremented day-by-day, starting at day zero, until 100% of fish arrived at the location being forecasted. Then, forecasted median run timing at the location was calculated as the date by which 50% of the fish had passed the location. Because the average stock entry distributions, the travel time from LYTF to Pilot Station sonar, and the reach-to-reach movement rates are the same for all years being forecasted, the only part of the forecast process that changes from year to year is the predicted median entry date.

Forecast Accuracy

Each piece in the forecasting process has some level of error associated with it, which is due in part to natural variation or process error, measurement error (e.g., in test fishery catches, or sonar counts), and model misspecification (Harwood & Stokes 2003, Hulson et al. 2011). In order to describe the potential degree of error for the entire forecast system, from the prediction of river entry timing all the way up to the prediction of inriver run timing for the Canadian stock along the main stem, we used a hindcasting approach to compare observed and predicted run timing at two locations along the main stem of the Yukon River: Rapids fish wheel and the Eagle sonar. In choosing the hindcasting approach, we arrived at a good estimate of how this method would have performed if it had been used in the past and we can extrapolate that performance to future years for which forecasts are desired. Unlike Eagle sonar, not all fish passing Rapids fish wheel are from the Canadian stock so forecasts of run timing at Rapids fish wheel were expected to be slightly less accurate than those for Eagle sonar.

An upriver cumulative run timing forecast was made for each year where observations of the components were available, namely 2000 – 2014 for Rapids fish wheel and 2005 – 2014 for Eagle sonar. For each year's predictions, only the data from years prior to the year of prediction were used to fit the entry timing model. The other parts of the forecast system (lag time between LYTF and Pilot Station sonar, the shape of the average stock entry timing distributions, and the parameters of the Inriver Model) were held constant. For example, to calculate prediction accuracy at Eagle sonar in 2007, we performed the following steps: (1) forecasted median entry timing using the best entry timing model fitted to years prior to 2007, (2) added in the historical average travel time between LYTF and Pilot Station computed for all years (3 days), (3) shifted the average stock entry timing distribution so its median run timing was equal to that forecasted in step 2, (4) predicted cumulative run timing and median run timing at Rapids fish wheel and Eagle sonar using the Inriver Model, and (5) calculated MAPE (and its SD) for the observed and predicted median run timings and graphically compared the observed and predicted run timing distributions.

Validation of the Inriver Model

The parameterization of the Inriver Model used in this study was based upon the assumption that fish always migrate identically to their movement during the three-year Eiler et al. (2014) study. In order to test the validity of this assumption, we used the un-normalized annual stock-specific run timing calculated previously, $\tilde{s}_{syd}$, in section 1.3.4 instead of the average stock entry timing distribution, in order to get a best estimate of the stock-specific run timing at Pilot Station sonar in year y. Predictions were made using the same hindcasting approach as before but were generated only for years with both genetic stock composition data and run timing data at the sonar site near Pilot Station. Run timing and median run timing were forecasted and median run timings were compared using MAPE (and its SD), and maximum absolute residual (MAR). If the structure of the Inriver Model and its parameterization are reasonable and fish tend to migrate as they did during the three-year Eiler et al. (2014) study, then prediction errors should be very low.

1.4 Results

1.4.1 Entry Model

Using hindcasting model selection (2000 – 2014) using MAPE, the width of the prediction interval, and the proportion of observed median entry timings within the prediction interval, the best model was the one containing all three explanatory variables (AIR, SST, and ICE). The best model had a MAPE of 1.80 days (SD 1.32 days), MAR of 6 days (Table 2; Figure 4), an average prediction interval (2 times model SE) of 4.6 days, and included the observed median entry timing in 80% of the years. We found a pattern of positive bias among the residuals though the cause is unclear. Other models with similar MAPE tended to have prediction intervals that included fewer of the observed median entry timings. The closest model to the best model was the one that included only SST; it had a lower MAPE (1.67) and a smaller prediction interval width (2.75 days), but the interval only included the observed median entry timings 60% of the time. Overall, the model selection criteria were very similar across models.

1.4.2 Inriver Model

Prediction Accuracy of the Inriver Model

For both upriver locations (Rapids fish wheel and Eagle sonar), the differences between observed and predicted median run timing were generally small, with predictions at Eagle sonar being slightly better than those at Rapids fish wheel (Figures 6, 7; Table 3). Rapids fish wheel had a MAPE of 2.33 days (SD 1.59 days), and MAR of 5 days. Eagle sonar had a MAPE of 2.00 days (SD 1.41 days), and MAR of 4 days. Interestingly, the increase in the magnitude of the three error metrics between river entry and Eagle sonar was not very large, even though the two locations are nearly 1600 km apart along the main stem of the Yukon River and the migration between the two locations takes roughly 31 days. This suggests that the largest source of forecast error is in forecasting median entry timing.

While forecast errors for median run timing were very low, forecast errors for the shape of the cumulative run timing distribution were quite variable. In some years (e.g. 2006, 2011 in Figure 8; 2004, 2012 in Figure 9) forecasts for median run timing and the shape of the cumulative run timing distributions were very similar to what was observed. In numerous other years, however, the shape of the forecasted cumulative run timing distribution was not a good match to the observed cumulative run timing distribution.

Validation of the Inriver Model

Differences between the observed and predicted median run timings were generally small, in the range of ± 1 day, with four of the eight available years having a difference of zero days (Figure 5, Table 4). The observed and predicted daily run timing distributions, which were compared graphically, generally had a high degree of similarity. These results supported our use of the

Inriver Model in pre-season forecasting and suggest that movement patterns of Canadian-origin Chinook salmon have not changed significantly over the last decade.

1.5 Discussion

In the present paper, we described a method and the application of a simple and general purpose movement model for forecasting stock-specific upriver migratory timing of Pacific salmon. Our method involved forecasting median entry timing for the run as a whole using an existing model from the literature, applying a model that we developed to convert the forecasts of median entry timing to forecasts of median entry timing for individual stocks, and finally applying a movement model to generate forecasts of stock-specific upriver run timing and median run timing. For the forecasts of upriver run timing, we used a hindcasting approach to approximate what would have happened if our method had been used in previous years. Forecasts for median run timing of the Canadian-origin stock at the US/Canada border were, on average, two days off, which is a low degree of error considering that the predictions would have been made weeks before the first salmon arrives at the river mouth. Along with the low error in median run timing forecasts at the US/Canada border, the size of forecast errors were similar at Rapids fish wheel, a site hundreds of kilometers below the US/Canada border but still considerably far upriver, suggesting that the magnitude of prediction errors may be similar for locations along the main stem and possibly throughout the river.

While forecast errors for median run timing were small, forecasts for the shape of the run timing were poor in in some years. Forecasting the shape of the run time distribution is equally as important to a manager as forecasting median run timing (Mundy, 1982). Forecasting the shape of the run timing distribution allows the manager to estimate when fish will start and finish arriving at a particular location, which could trigger the opening or closing of fisheries. The reason for the poor forecasts of shape is most likely due to using an average when the shape varies considerably from year to year, rather than forecasting the shape in each year directly. In previous work, we investigated covariates of the shape of these run timing distribution and was unable to find a strong enough relationship to be useful in forecasting. Forecasting the shape of the run timing distributions is certainly a key area for future research on the Yukon River and elsewhere.

We calculated forecast errors for upriver median run timing using MAPE, which is a measure of average error. While we also calculated the worst prediction for each upriver location (MAR), it impossible to know in-season whether the current year is one of those poor prediction years until the run is over. For forecasts of upriver median run timing, errors in pre-season forecasts have the potential to accumulative because the forecasts are made serially, each forecast feeding into the next. In this study, there may be error in (1) forecasting the date of median entry timing, (2) the travel time between LYTF and Pilot Station sonar, (3) error in both the shape of the average stock entry timing distributions and its location (median), (4) and error in the stock-specific movement rates. Sources of errors are not only limited to process errors, as outlined above. At each location where forecasts of either median run timing or run timing are made (LYTF, Pilot Station sonar, Rapids fish wheel, Eagle sonar), measurement errors may lead to errors in interpreting in-season data and lead the manager to conclude a pre-season prediction is far off.

The last source of errors is in model specification, the greatest of which is the average stock entry timing distributions, which assumes the shape of the average stock entry timing distribution at Pilot Station sonar in any given year is average, when in reality the data do not support this assumption. Errors resulting from this assumption could result in an increase of forecast errors for inriver median run timing of numerous days. Despite the long list of potential sources of error, we found that our forecast of upriver median run timing were accurate on average and that the worst forecast error from either of our two sites was only roughly twice the magnitude of the average forecast error.

These models represent the first quantitative modeling framework for forecasting stock-specific inriver run timing for the Yukon River Chinook salmon run. Given the previously-mentioned limitations of the pulse-based system, these models provide managers with an objective tool to use in managing the fishery that is stock-specific and potentially more accurate than the current system. Compared with managing based upon pulses, this modeling framework has two main advantages: First, it can be used to generate pre-season forecasts which are useful for pre-season planning. Second, by expressing forecasts in terms of run timing and median run timing, predictions from this framework can be used in future modeling work.

For many salmon runs subject to fisheries management, forecasts of run timing are relatively uncommon compared to forecasts of run size. Inferences about whether the run size is smaller, the same, or larger than the pre-season forecasts are often made using in-season catch, test fishing, and escapement data (Fried & Hilborn 1988, Su & Adkison 2002) but this inference is tightly linked with expectations around run timing (Anderson & Beer 2009, Adkison & Cunningham 2015). When uncertainty exists around both run size and run timing, a manager may not be able to tell the difference between a small run size with early run timing and a large run with late run timing, although the two scenarios may require vastly different management approaches (Adkison & Cunningham 2015). When paired with commonly present pre-season forecasts of run size, pre-season predictions of run timing have the potential to reduce uncertainty around run size, providing a useful source of inference for the manager.

In the case of the Yukon River Chinook salmon run, median entry timing can be forecasts accurately using our method and the relationship between catches at LYTF and total run size could be modeled from historical data. As a result, in-season forecasts about the total run size could be made before half of the run has even entered the first fishing, allowing managers to adjust the length and location of fishing openers. Even used alone, pre-season forecasts of run timing at upriver locations can allow managers to let users know ahead of time when a district closure may be needed in order to increase the probability of meeting escapement goals.

While the models outlined in this paper are specifically tailored to the Yukon River Chinook salmon run, modifications to accommodate other stocks are simple to implement given sufficient data. The most important criterion that will determine the modifications necessary is whether upriver run timing predictions are needed on a stock-specific basis, as in the present study. If so, one would need either a median entry timing forecasts that was stock-specific or a model to convert a median entry timing prediction for all stocks into median entry timing predictions for each individual stock (as was done in the present study). Stock-specific movement rates would also be needed; though the same movement rates could be used for all stocks if stock-specific estimates were not available but stock-specific differences in run timing needed to be modeled. Movement rates are often established using radio telemetry, as was done in Eiler (2014, 2015) or by other tagging methods and these types of studies present suitable estimates. The Inriver Model is general and can be applied whether single or multiple movement rates are available. Because of the simple nature of the Inriver Model, it is computationally inexpensive to run repeated predictions for the same stock and upriver location. This makes our method suitable for use in a management strategy evaluation (MSE) framework as has been done for Yukon River chum salmon (Criddle & Streletski 2000). Together, this method is general enough that it can be applied to numerous salmon stocks or stock complexes that migrate into large river systems.

1.6 Acknowledgements

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1.8 Tables

Table 1. Dates and sample sizes (n) for the reporting periods of genetic stock composition estimates from the Pilot Station sonar project. Note: There was a fourth reporting period in 2009 from June 23 to July 19 (n=145) which was not shown here for space considerations.

	Period 1			Period 2			Period 3		
Year	**Start**	**End**	**n**	**Start**	**End**	**n**	**Start**	**End**	**n**
2007	June 6	June 19	214	June 20	June 30	138	July 1	July 17	188
2008	June 7	June 23	333	June 24	June 29	155	June 30	Aug 2	223
2009	June 9	June 16	133	June 17	June 22	309	June 23	June 29	280
2010	June 12	June 21	99	June 22	June 27	132	June 28	July 17	139
2011	June 1	June 18	190	June 19	July 27	196	June 28	July 26	177
2012	June 10	June 24	138	June 25	July 25	196	July 3	July 23	106
2013	June 14	June 23	115	June 24	July 2	95	June 29	July 10	114
2014	June 1	June 11	125	June 12	June 20	168	June 21	June 27	126

Table 2. Model selection results for the six candidate models for forecasting median entry timing for Yukon River Chinook salmon. MAPE refers to mean absolute prediction error, INTWIDTH is equal to twice the model standard error, and PROP is the proportion of forecasted median entry timings within the interval INTWIDTH. Best values are shown in bold and best model is listed in bold.

Model	MAPE (days)	INTWIDTH (days)	PROP
MDJ ~ AMATC	3.80	3.05	0.47
MDJ ~ MSSTC	**1.67**	**2.75**	0.60
MDJ ~ PICE	2.73	3.39	0.40
MDJ ~ AMATC + MSSTC	1.93	3.35	0.60
MDJ ~ AMATC + PICE	3.13	4.23	0.40
MDJ ~ MSSTC + PICE	1.87	3.85	0.60
MDJ ~ AMATC + MSSTC + PICE	1.80	4.55	**0.80**

Table 3. Residuals from hindcasted forecasts of median run timing at three locations and corresponding estimates of mean absolute prediction error (MAPE), its standard deviation (SD), and the maximum absolute residual (MAR) at each location. Forecasts at LYTF were generated using the Entry Model and forecasts at Rapids and Eagle were generated using the Upriver Model. Run timing data for Eagle were not available from 2000 – 2004.

Year	LYTF (days)	Rapids (days)	Eagle (days)
2000	3	-4	N/A
2001	-1	-1	N/A
2002	2	-5	N/A
2003	-2	2	N/A
2004	1	1	N/A
2005	1	-1	-3
2006	1	-5	0
2007	2	2	-1
2008	2	-1	2
2009	-1	-3	-4
2010	1	-1	1
2011	-1	-2	-1
2012	6	0	1
2013	1	-3	-4
2014	2	-4	-3
MAPE	1.80	2.33	2.00
SD	1.32	1.59	1.41
MAR	6	5	4

Table 4. Differences between the observed and forecasted median run timing at Eagle sonar using the un-normalized annual stock-specific run timing at Pilot Station (2007 – 2014). Positive values indicate that the observed median run timing was later than forecasted.

Year	Residual (days)
2007	0
2008	-1
2009	-7
2010	1
2011	0
2012	0
2013	1
2014	0
MAPE	1.25
SD	2.38
MAR	7

1.9 Figures

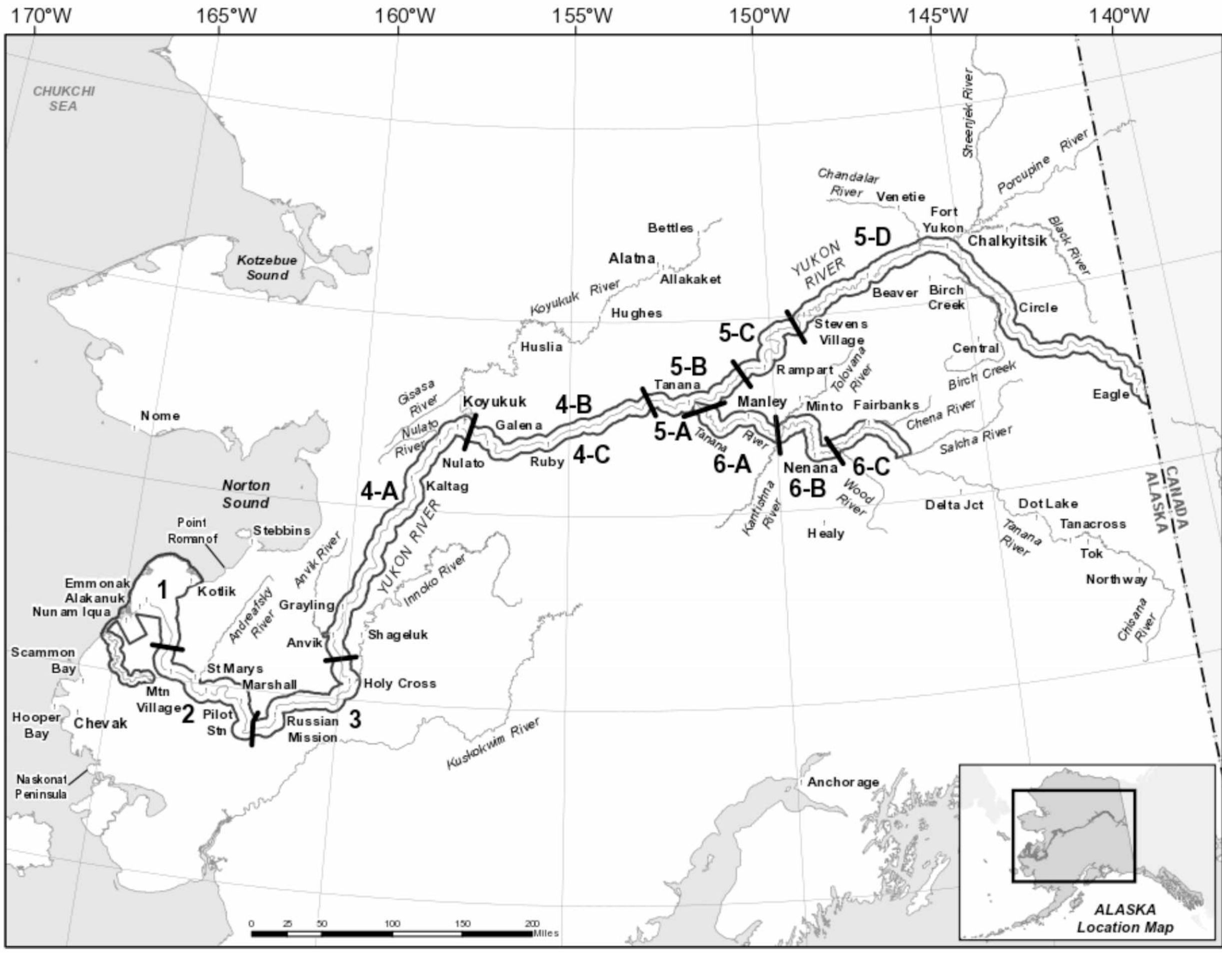

Figure 1. The Alaskan portion of the Yukon River showing the seven principal management districts. Reprinted with permission from Estensen et al. (2015).

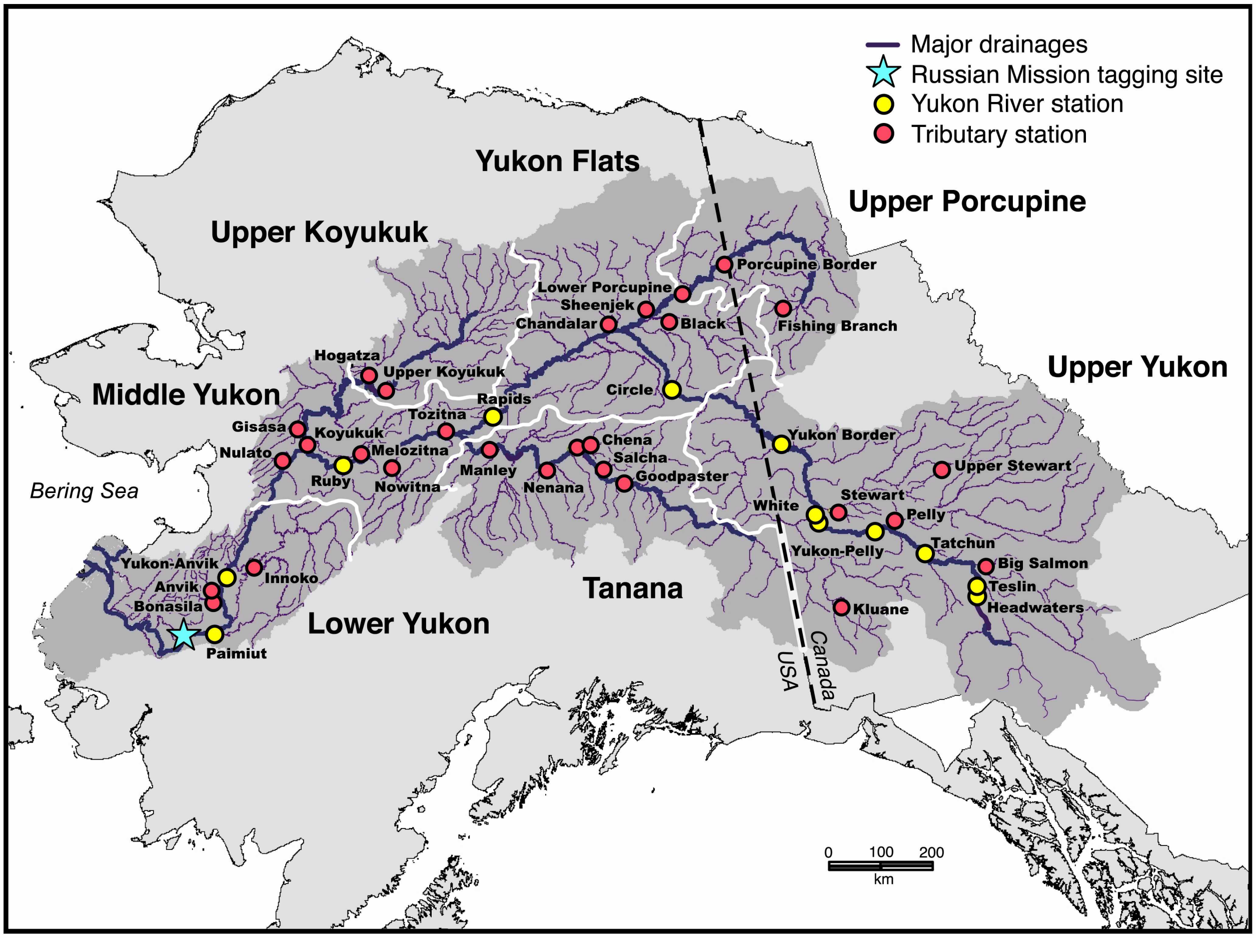

Figure 2. Map of the Yukon River drainage showing the tagging site (star) and main stem Yukon River tracking stations (open circles) which correspond to the reaches used in this study. Reprinted with permission from Eiler et al. (2015).

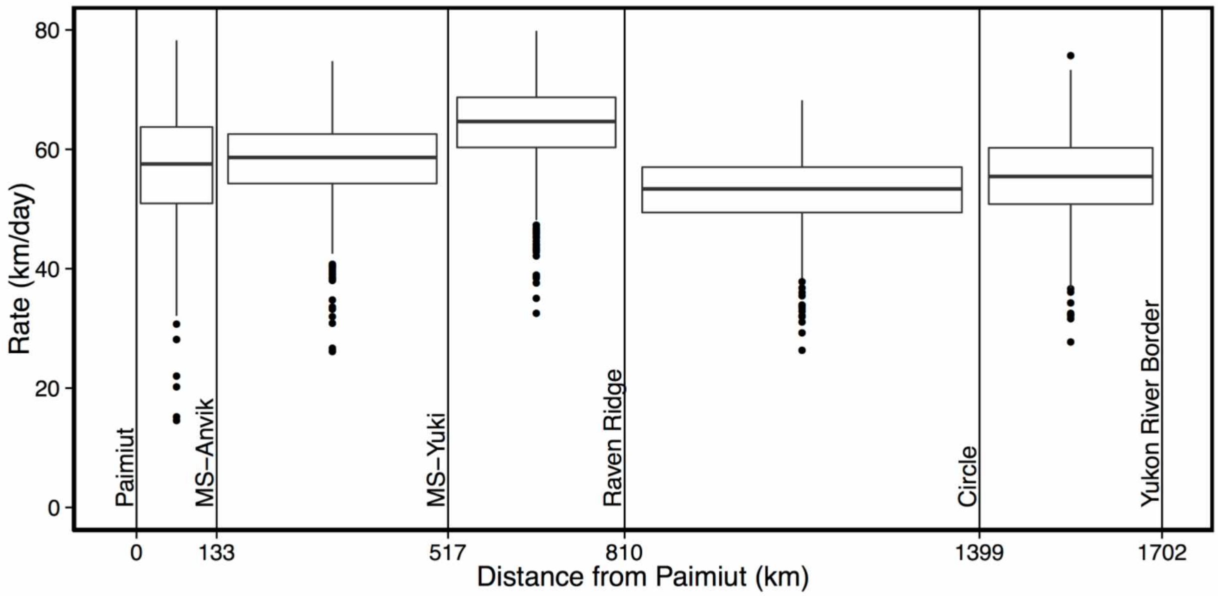

Figure 3. Reach-to-reach movement rates for individual Canadian stock Chinook salmon from Eiler et al. (2014, 2015). Vertical lines with titles mark the location of satellite-linked remote tracking stations used in Eiler et al. (2014, 2015).

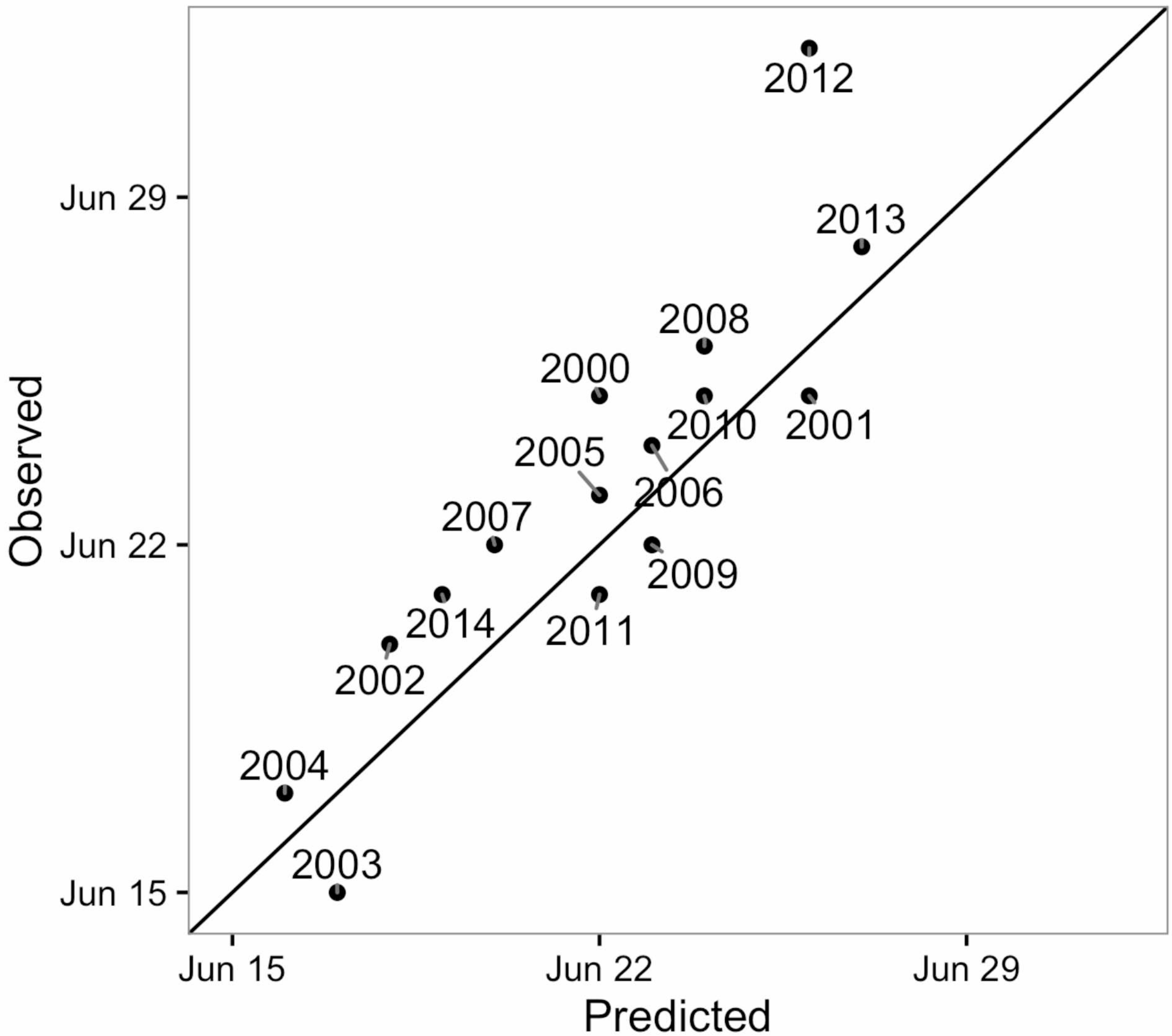

Figure 4. Observed and predicted median entry timing of Chinook salmon entering the Yukon River (2000 — 2014) calculated using the Entry Model.

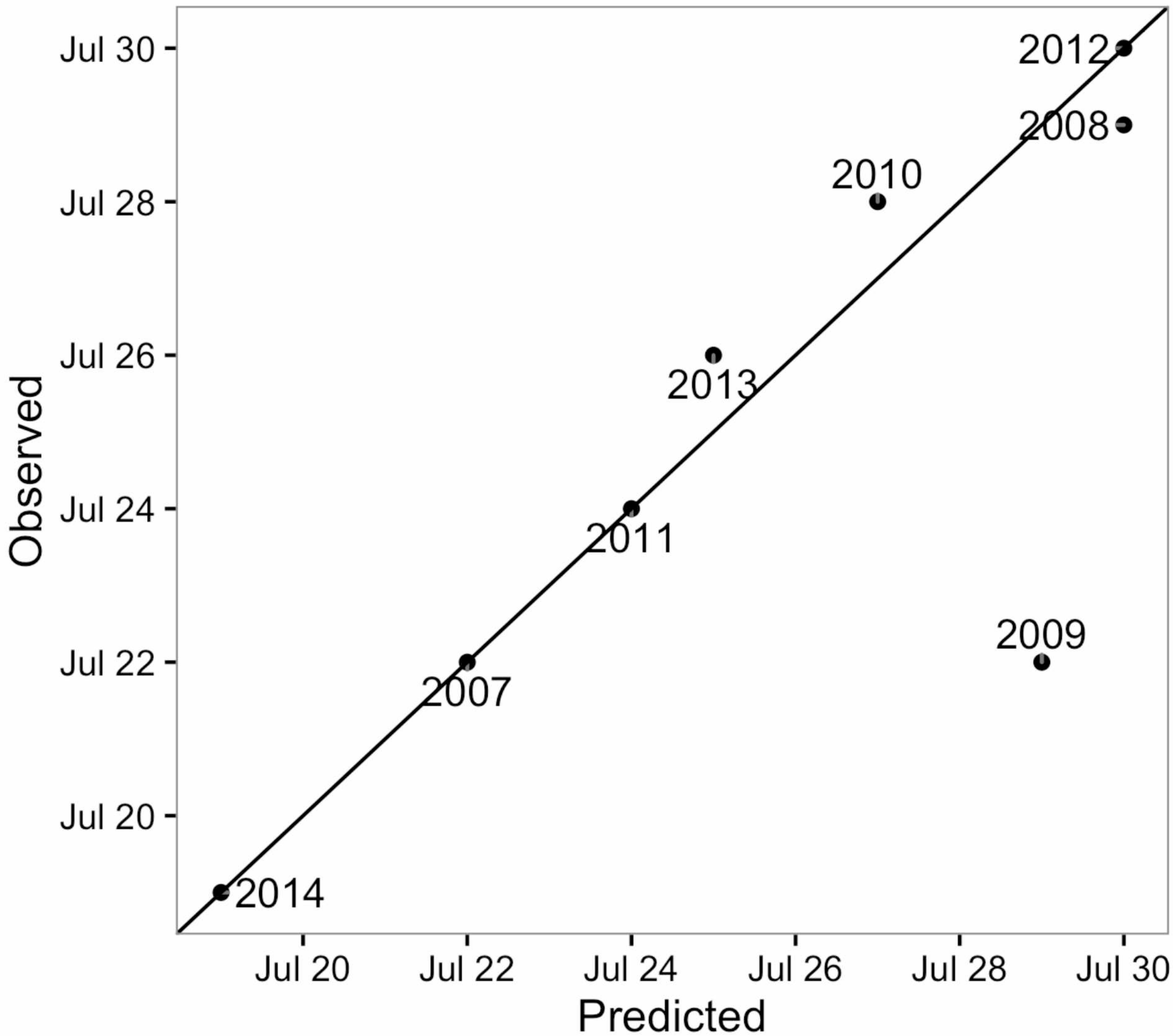

Figure 5. Model validation results showing the low error in forecasting median run timing at Eagle sonar (2007 – 2014, except for 2009) using the un-normalized annual stock-specific run timing at Pilot Station rather than a pre-season forecast. The large, negative residual in 2009 is potentially due to an inaccurate estimate of run timing at Pilot Station in 2009.

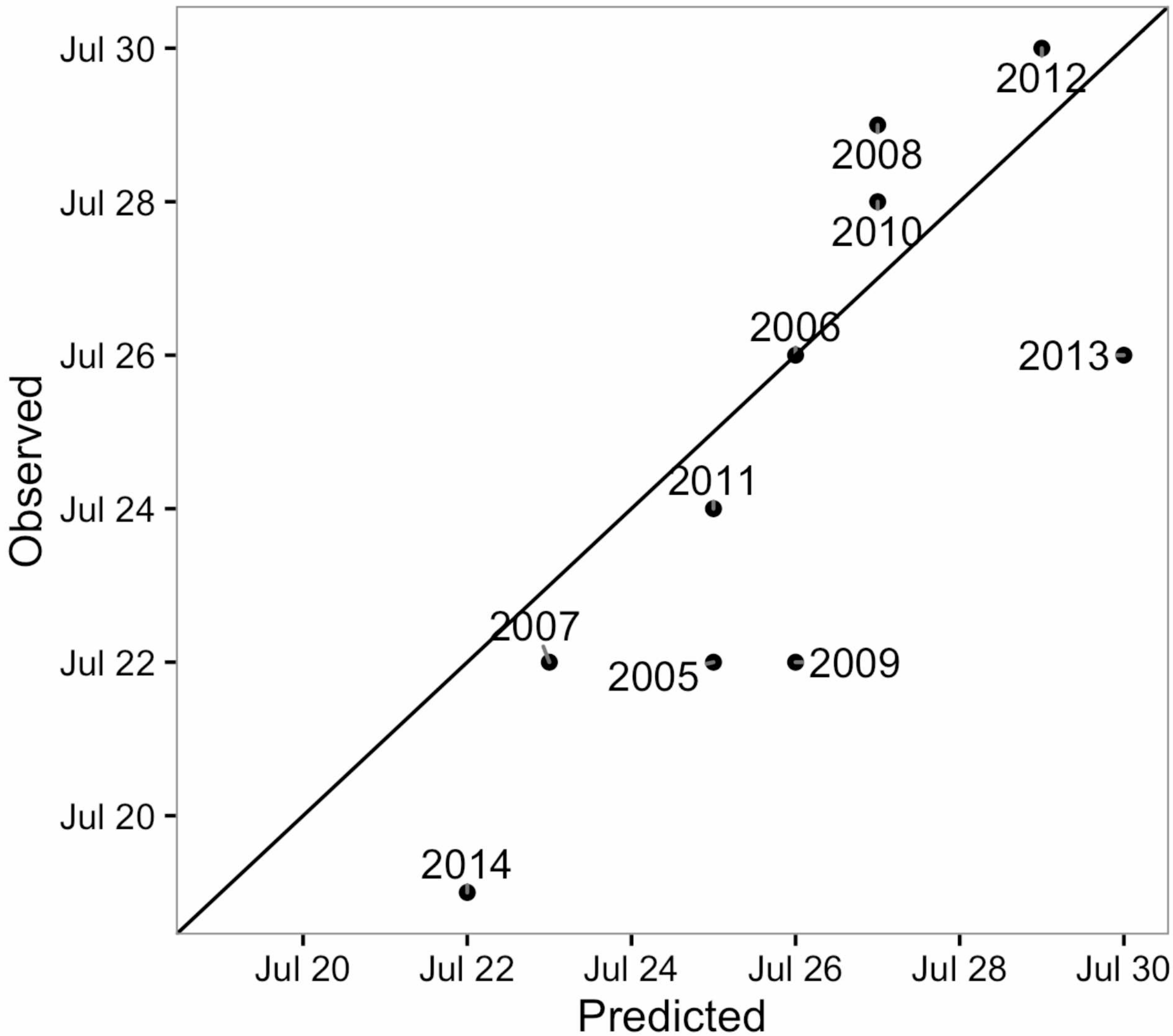

Figure 6. Observed and predicted median run timing at Eagle sonar (2005 – 2014) generated using the Inriver Model.

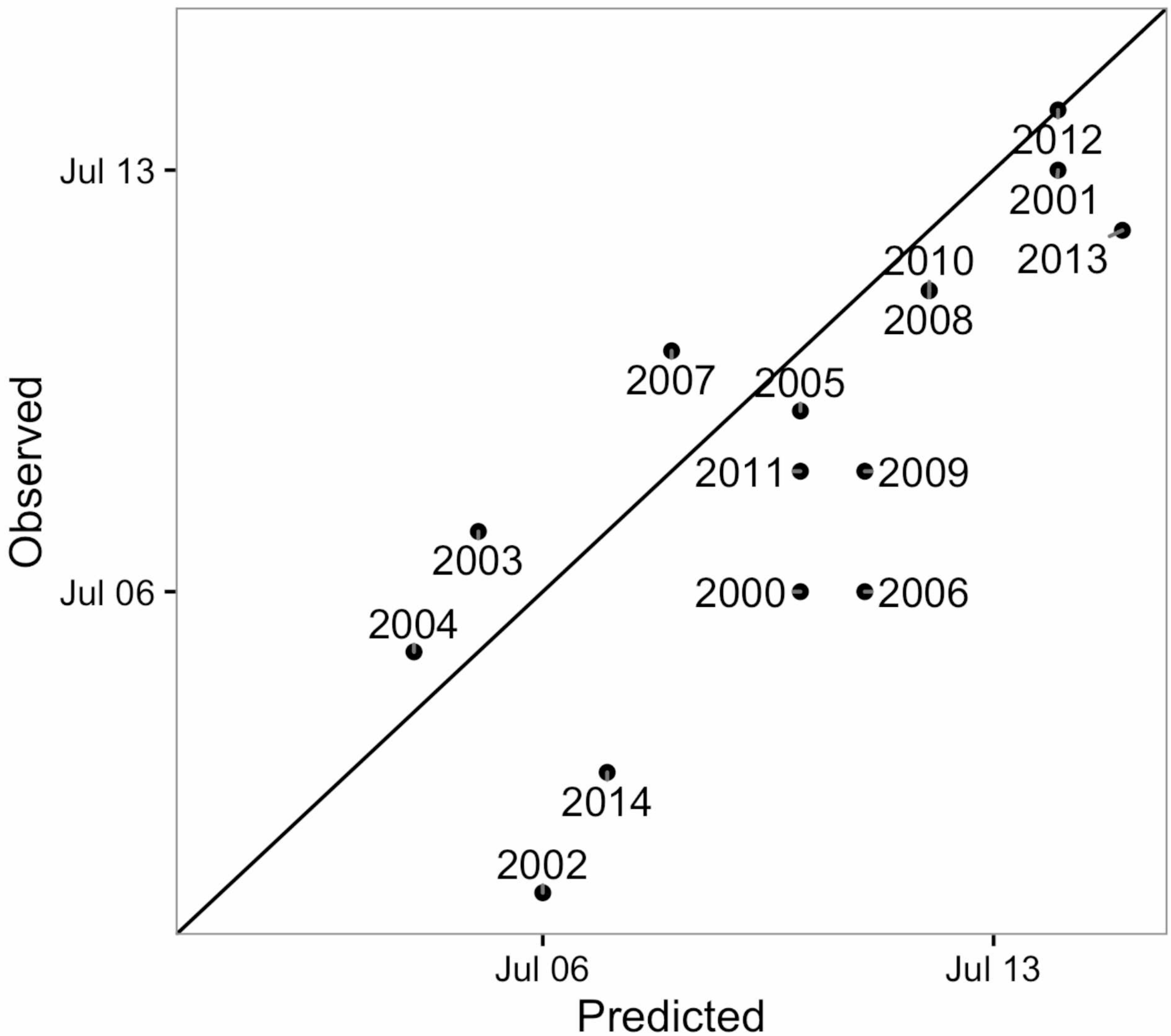

Figure 7. Observed and predicted run timing at Rapids fish wheel (2000 – 2014) generated using the Inriver Model.

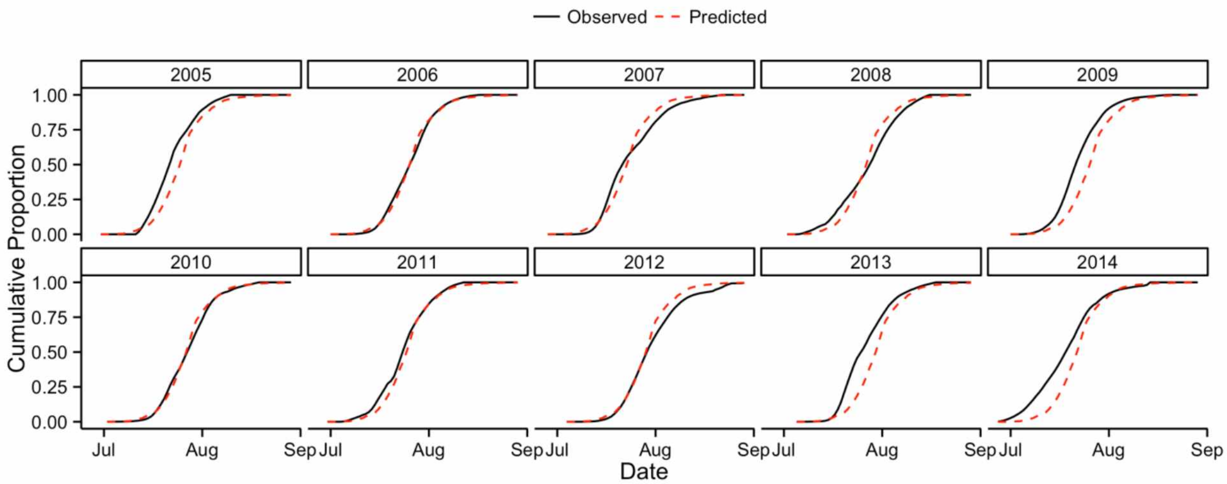

Figure 8. Observed and predicted run timing at Eagle sonar (2005 – 2014) generated using the Inriver Model.

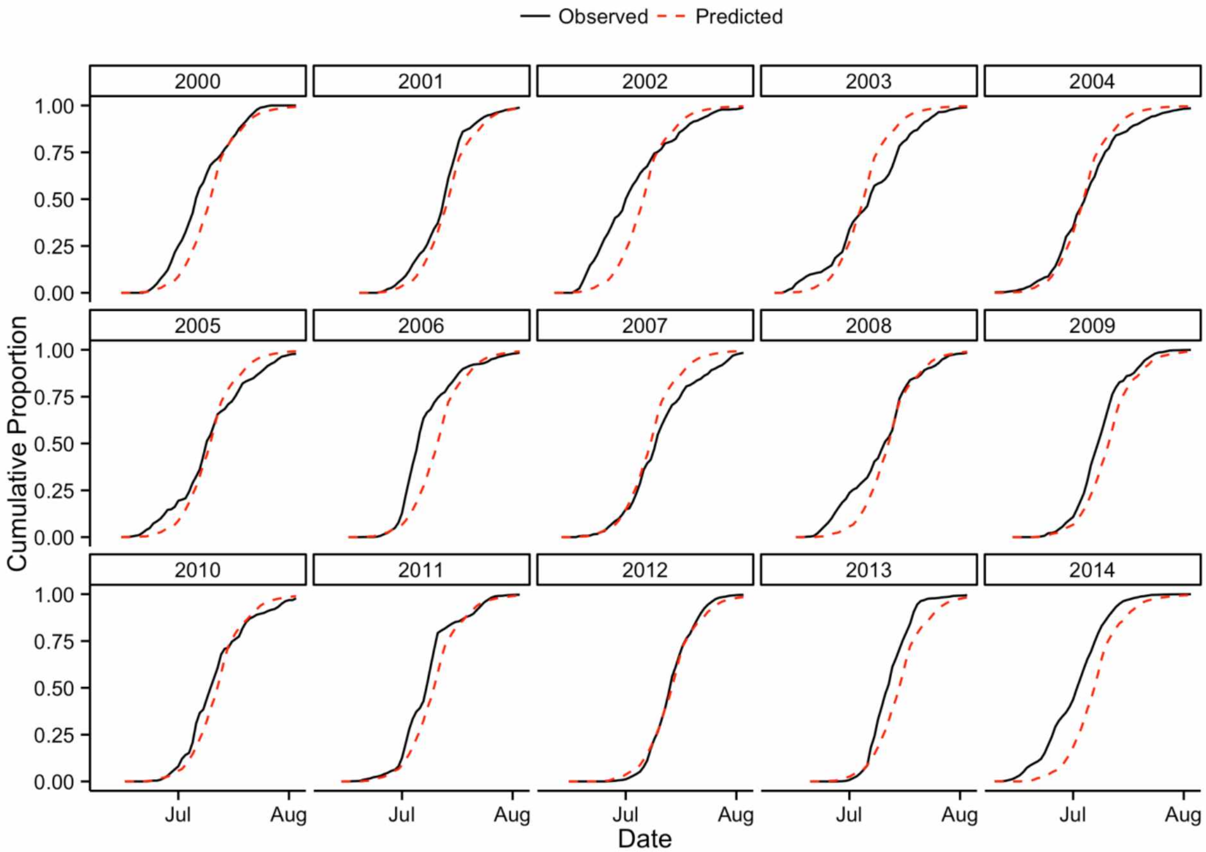

Figure 7. Observed and predicted run timing at Rapids Fish Wheel (2000—2014) generated using the Inriver Model.

Conclusion

Run timing plays an important role in salmon management because it impacts decisions such as when and where fishing takes place, how processing plants manage staff and their inventory, and how managers make pre- and in-season inferences about run sizes, which plays an important role in achieving harvest objectives. Harvest objectives include achieving spawning escapements within escapement goal ranges or above minimums and achieving desired allocation goals across gear types and user groups. The ability to predict the run timing before fish arrive has the potential to increase the probability of achieving these types of harvest objectives, thereby improving the long-term sustainability of fisheries as well as the humans who fish in them. Without a statistical model with which to predict run timing, managers must base predictions on long-term averages and wait for a substantial number of fish to transit harvest areas before making management decisions. A model such as the one presented in this thesis predicts run timing with significantly lower error than using long-term averages; thus, it is a useful management tool.

Understanding and forecasting run timing is increasingly important due to interannual variation mediated by climate (Quinn & Adams 1996, Hodgson et al. 2006, Kovach et al. 2013). Global climate change is expected to result in increased atmospheric temperatures and increased prevalence of abnormal weather events (IPCC 2013). The pre-season entry timing model used in Mundy & Evenson (2011) and in this thesis uses three climate-mediated variables (air temperature, sea surface temperature, and ice cover) and its use as a management tool is thus affected by global climate change. With increased temperatures, we can expect earlier migrations because warmer temperatures correlate with earlier migrations (Mundy & Evenson 2011). We can also expect more migrations with unusual timing as future observations fall outside their historical ranges. Thus, having standardized methods can aid in better predictions when those changes occur. With all of the difficulties in predicting run timing in a rapidly changing environment, quantitative tools such as the ones created in this thesis make it possible to understand and predict the impacts of higher air and sea surface temperatures on run timing. They may also serve as the basis for improved models to supplement or replace them.

While the model developed in this thesis performed well when applied to a model system and showed potential as a management tool, there are three main limitations to address for future improvement. First, the model is not statistical and therefore does not inherently take into account uncertainty in its components nor does it produce estimates of uncertainty for predictions made from it. Ideally, we'd like to know the probability of a particular run timing outcome, a question which fits well into a Bayesian estimation framework. We were able to partially work around this limitation by using hindcasting. Second, the model cannot take advantage of in-season data. That said, we did not identify an existing in-season data source the model could take advantage of, but one may exist or be created in the future. Third, the model does not include a component that predicts the shape of the arrival or upriver run timing distributions. Prediction errors for median run timing were low but prediction errors for the shape of the run timing distributions were low in some years and high in others. Managers benefit from accurate predictions of the shape of the run timing distribution as well as the median, therefore better predictions of this would be a beneficial expansion of this work.

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Appendix

The following list is an abridged glossary of terms used in this thesis. The purpose of this glossary is to serve as a reference for new terms that I have defined and to clarify my use of a set of pre-existing terms that may be ambiguous.

reach – An uninterrupted length along a river.

run timing – A time series of counts, proportions, or index values (such as catch-per-unit-effort) describing the abundance over time of fish passing a location.

median run timing – The date on which 50% of the total run has passed a location.

entry timing – Run timing measured at or near a river mouth.

inriver run timing – Run timing measured at sites upriver of a river mouth.

in-season – A period of time prior to the arrival of the first fish at or near a river mouth.

preseason – A period of time after the arrival of the first fish at or near a river mouth.